Water Use and Sustainability in the Tucson basin: Implications of Spatially Neutral Groundwater Management

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0. Introduction

Arizona has developed strong regulatory mechanisms to ensure long-term sustainable water use, and to integrate land and water use planning for the most populated areas (*Jacobs, 2009*). The sustainability objective in Arizona's water policy is based on the concept of "safe yield"; i.e., that the extraction of groundwater on a basin-wide and long-term basis is no more than is naturally and artificially recharged. This concept has been criticized by hydrologists, because it can be interpreted as implying that by achieving a balance between recharge and pumping results there will be no detrimental impact on the aquifers and their dependent systems (*Zhou, 2009*). As a sustainability objective, the concept of safe yield may be considered as rather reductionist because it refers exclusively to the flows in and out of an aquifer, without taking into account other hydrogeological, socioeconomic and ecological criteria. Further, although limited, safe-yield as a management goal is nevertheless challenging to both implement and evaluate.

Until the arrival, in 1992, of Colorado River water through the Central Arizona Project (CAP) (see supra chapter 6 p.§§), the city of Tucson and surrounding municipalities depended solely on groundwater for their water supply. As in other rapidly growing areas of Arizona, intensive groundwater pumping resulted in significant decreases in groundwater level and in consequent subsidence of areas of land. Approval of the Groundwater Management Act (1980), and the resulting transformation of the institutional context for water management in Arizona, had introduced changes in the way groundwater was managed and used in the Tucson basin. These included restrictions in water use patterns for municipal, industrial and agricultural users, through binding conservation programs. The arrival of CAP water brought a new water source to the region that helped to substitute for diminishing groundwater resources. A recharge and recovery program was created to manage the new "renewable resources"[1] that came with the CAP, thereby allowing the region to optimize water allocation by storing large volumes of Colorado River water underground, in overexploited aquifers.

The Tucson basin is now recognized as a reference for its conservation practices to curb demand and its innovative groundwater management system (*Jacobs & Holway, 2004;*

[1] The Arizona water community uses the term "renewable resources" to refer to the inflow of Colorado River water through the CAP. However, the consideration of Colorado water as renewable is questionable given the serious impacts that this interbasin transfer, coupled with all the other ones that the Colorado suffers, causes in the donor river basin, the severe drought-related variability of water availability, the uncertainty surrounding climate change predictions and the amount of energy required to pump Colorado water all the way to the Tucson basin.

Megdal et al., 2014). However, these practices are not exempt from critical assessment, since the techno-social fixes they present avoid facing the core challenge of uncontrolled urban growth head-on (*Hirt et al., 2008; Akhter et al., 2010*). To our knowledge, two elements of Tucson's water management system have not yet been evaluated: a) the impacts of water conservation programs on overall demand, and b) the spatial dynamics of the groundwater management system.

This chapter reviews the state of the art of current debates around sustainability objectives in Arizona water policy, with a focus on the Tucson basin area. The review was undertaken via a dialogue between water researchers and managers from Arizona and Spain, two different regions where the hydraulic paradigm has dominated water management practice (*Reisner, 1993; Sauri & Del Moral, 2001*). We analyze available data on water use and groundwater management, and compare it with other socioeconomic and environmental variables in order to provide insights into the limitations and challenges of current strategies to achieve safe yield. Specifically, we examine three relevant questions identified in collaboration with local stakeholders:

1) How has the water metabolism evolved since the approval of the GMA and the arrival of the CAP to the Tucson Basin?
2) Is water demand decreasing as a result of conservation programs?
3) How does the spatially neutral approach to groundwater management shape vulnerabilities in the socio-hydrological system?

This research uses a quantitative approach to the analysis of sustainability that builds on the concept of societal metabolism (*Giampietro et al., 2009, 2011, and 2014*) and is complemented by a thorough review of the academic literature and water planning reports, interviews with local experts, and participant observation of water planning meetings. The investigation was conducted in two phases, between February and July of 2013, and between November 2014 and March 2015. While a deeper understanding of the debate around sustainability in water governance in Arizona would require additional analysis of power relations than is undertaken here (se *supra* chapter 7 p.§§), the insights we gained can contribute to the discussion of ongoing and future water management challenges in the state.

The chapter is organized into five sections. First, we describe the institutional context for water management in Arizona. Then we introduce the conceptual framework and the methodology used. Section 4 discusses the results structured as i) A historical perspective on water use and planning; ii) A description of the evolution of the societal metabolism of water after the arrival of CAP; iii) A discussion of the interplay between conservation programs and water demand; and iv) A spatial analysis of groundwater dynamics. We conclude with a discussion of the effectiveness of current water management strategies to cope with long-term and spatially equitable[2] sustainability.

1. Characteristics of the Tucson basin

[2] Equity implies a social or political consensus about the 'fairness' or 'justice' of the distribution of costs and benefits of a policy or program. Yet achieving a consensus concerning the fairness of a particular distribution is almost impossible. Thus, equity is a complex and value-laden concept (Truelove, 1992). However, the notion of 'spatial equity' enjoys a long tradition in spatial planning practice. In a physical sense, spatial equity can be understood as the equitable development of land use. In a socio-economic sense it can refer to the equitable flow of goods and services from one spatial arena to another. In both senses, spatial equity is a parameter for sustainable development and can be defined as both a process and an outcome. As process, it involves the redistribution of the overall resources and development opportunities and/or the optimization of locally existing resources and development opportunities of an area. As an outcome, it envisions a region or area where such redistribution or optimization is achieved and sustained (*Buhangin, 2013; Kunzmann, 1998*).

The Tucson basin is constituted by two wide alluvial valleys, bounded by mountain ranges, in which the city of Tucson (Pima County) is located. The basin overlies the interconnected aquifers of the Avra Valley and the Santa Cruz River (Figure 1), and this delimitation is used by for water planning by the Arizona Department of Water Resources (ADWR), which established the Tucson basin as a management unit (the Tucson Active Management Area, or TAMA, via the 1980 Groundwater Management Act. The Santa Cruz River used to flow in a Southeastern-Northwestern direction, as did the groundwater flow of the underlying aquifer, until aquifer overdraft caused the water table to drop and the river to dry up during the second half of the 20th century. Most of the runoff and aquifer recharge originates from higher precipitation rates along the mountain front during both winter rainfall and monsoon summer storms. Ephemeral channel recharge from storms in the basin can also be significant. After Phoenix, the TAMA is the second most populated region in Arizona, with a total population of one million people distributed over four main urban areas (City of Tucson, and the towns of Marana, Oro Valley and Sahuarita), other urban sprawl areas (Census Designated Places) and parts of the Tohono O'odham Nation.

(Figure 1 to appear here)

Figure 1 A - Tucson basin location and groundwater levels. B – Urban areas

2. Institutional context for water management in Arizona

The evolution of water law and management in Arizona has been characterized by an ongoing effort to augment water supplies to support unconstrained economic and population growth (*Waterstone, 1992; Akhter et al., 2010*). The institutional context for water management consists of a complex system of regulations, norms, agencies and public and private operators that have evolved over time in response to changing socioeconomic, political and technological realities.

Groundwater use in Arizona was largely unregulated until the approval (in 1980) of the Groundwater Management Act (GMA) (*Gastelum, 2012*), while surface water law is governed by the prior appropriations doctrine. Before 1980, groundwater abstractions were only limited by the reasonable use doctrine (*Jacobs, 2009*). Starting in the 1940s, strong socioeconomic and population growth resulted in significant aquifer overdraft and land subsidence. By the 1970s it was clear that something had to be done to regulate groundwater pumping. In 1976 the Arizona legislature created a groundwater commission to write a groundwater law, but political resistance from agricultural users (who held a majority of groundwater rights) prevented any proposal from advancing. Negotiations finally succeeded when the Federal Government conditioned the approval of funding for the construction of the Central Arizona Project (CAP) to the passing of groundwater management rules in Arizona (*Akhter et al., 2010*).

The GMA designated four Active Management Areas (AMAs) in parts of the state where groundwater pumping was particularly intense around major urban and agricultural areas (see *Figure AMAs p.XX*). A groundwater management goal was established in each AMA, to be achieved by 2025 through the implementation of 5 consecutive management plans (MPs). The management goal for the Phoenix, Tucson and Prescott AMAs is to achieve safe yield. The goal for the Pinal AMA is to maintain the agricultural-based economy for as long as possible. In 1995 a portion of the Tucson AMA was separated out and became the Santa Cruz AMA. Its management goal is to maintain safe yield and prevent local water tables from experiencing long term declines.

Within the AMAs, existing groundwater uses prior to 1980 received a "*grandfathered right*", and a moratorium on new irrigated agricultural land was imposed (*Megdal et al., 2014*). Management plans for each AMA established mandatory conservation goals for groundwater users that apply to most non-exempt wells (wells that pump in excess of 35 gallons/minute or 70.000 m^3/year) in the agricultural, industrial and municipal sectors (*Jacobs, 2009*). The GMA established clear guidelines for the first three MPs but was vague on the requirements for the 4th and 5th, given the uncertainties associated with such a long-time planning horizon. Finally, the GMA created the ADWR, centralizing all quantity-related water management responsibilities.

The three first MPs (1985-1990, 1990-2000, and 2000-2010) followed specific guidelines established in the GMA. As of October 2015 (when this paper was completed) the IV MP had not yet been and the III MP's rules continue to apply. MPs are primarily regulatory documents establishing conservation programs for the different sectors (municipal, agricultural and industrial). They are not true management plans in the sense of roadmaps towards achieving objectives (*Megdal et al., 2008: 35*). Management per se is done by providers in a decentralized governance regime, without regional (basin scale) common planning over resources allocation.

The CAP is the primary source of renewable water supplies in central Arizona. Every year it delivers 1.6 MAF (1900 Mm^3) of Colorado River water to portions of the Phoenix, Pinal and Tucson AMAs (Prescott and Santa Cruz AMAs do not have access to CAP water), representing 57% of Arizona´s 2.8 MAF entitlement of Colorado River water. The Central Arizona Water Conservation District (CAWCD) was created to manage and operate the CAP and generate the resources to repay the federal government for the investment. To help ensure long-term water supply, given that Arizona's CAP water entitlement exceeded instate demand, a groundwater recharge and storage system was devised to utilize Arizona's surplus water and firm its supply from Colorado River water. Those entities that recharge water get groundwater recovery credits for the future. There are two mechanisms for credit generation:

- Underground Storage Facilities (USFs): These are areas where CAP or reclaimed water is physically recharged, either through constructed injection wells or recharge basins, or other managed recharge mechanisms, by a diversity of private and public operators. This water can then be recovered (pumped) in the form known as CAP/reclaim recovered water.
- Groundwater Saving Facilities (GSFs): Also called in-lieu or indirect recharge, these are locations where CAP water or effluent is primarily used by irrigation districts instead of their irrigation groundwater rights. The surface water provider gets a groundwater credit for the amount of water that would have otherwise been pumped.

The program distinguishes between water stored for recovery in the same calendar year (recovered water or short-term credits) or in a later year (long-term storage credits). In the latter case, 5% of each acre-foot of CAP water recharged or not extracted is considered to be the "*cut to the aquifer*", devoted to overdraft recovery. In the case of reclaimed water the cut to the aquifer is 50% if it is recharged via a managed facility, while reclaimed recharge from constructed facilities has no cuts.

Given the expectation that the municipal water sector would continue to grow, the Assured Water Supply (AWS) program was created to link water and land use planning (*Jacobs, 2009*). The draft rules set by the ADWR in 1988, that restrict allowable groundwater declines, encountered strong opposition from the development community, agricultural sector and cities without CAP access (*CAGRD, 2014: 17*). The outcome was the AWS program, a new rules package (approved in 1995) that requires all new urban developments to provide proof of physical, legal, and continuous access to a 100-year supply of water.

The Central Arizona Groundwater Replenishment District (CAGRD) was created in 1993 to facilitate municipal water users meeting the AWS rules. It encompasses the Phoenix, Tucson and Pinal AMAs. Membership in CAGRD allows landowners and water providers without access to CAP water or other renewable supply to use mined groundwater to prove AWS. Members pay the CAGRD to replenish any water pumped in excess of AWS rules. The CAGRD thus serves a double function of firming larger amounts of CAP water while at the same time facilitating development and growth in the AMA regions by ensuring 100 years of water supply to those municipal users outside CAP service areas. The CAGRD has priority over the recharge capacity of CAWCD sites (*CAGRD, 2014: 11*).

A final but important piece of the institutional puzzle for water management at the state level is the Arizona Water Banking Authority (AWBA), created in 1996 with the double purpose of allowing intrastate and interstate water banking and of facilitating the firming of Arizona's full Colorado water entitlement. Funding for the operation of the AWBA comes from a property tax on all real-estate owners in the 3 CAP counties (Maricopa, Pinal and Pima), and from a fee on groundwater pumping and state appropriations (*Megdal et al., 2014*). Until December 2013 AWBA had spent $207.9 million and stored 3897 MAF (4806.9 Mm^3) in long-term storage credits, the majority in Phoenix and Pinal AMAs (*AWBA, 2013*). AWBA does not hold rights and it does not operate a water market. It also does not own or operate storage facilities and is not responsible for recovering the water it stores—the CAP recovers the water in times of shortage (*Jacobs, 2009*). The target of the AWBA is to store up to 3.6 MAF (4493 Mm^3) to ensure long-term municipal uses in times of shortage (*AWBA, 2013*).

The ADWR regulation functions are mainly related to conservation programs, data collection, water accounting and information generation and technical support to regional water management processes within the AMAs (*ADWR, 2015b*). The GMA established Groundwater Users Advisory Councils (GUAC) in each of the AMAs to act as intermediaries between the multiple parties involved in the water management networks and the ADWR and AWBA. The Tucson AMA is an acknowledged example of active regional cooperation. Besides the GUAC, several initiatives have been undertaken in the last 15 years analyzing and promoting regional water policies. The Institutional and Policy Advisory Group (IPAG) was specifically formed to develop the recharge plan for the TAMA in 1995[3]. Recently, a new working group called the Safe Yield Task Force was created to coordinate efforts towards the achievement of the AMA's management goal.

3. Methods

The objective of this chapter is to delve into the debates about sustainability of water management in the TAMA, focusing on three specific issues: 1) the changes in the water metabolism driven by the GMA and the arrival of CAP water to the TAMA; 2) the effects of conservation programs on water use; and 3) the spatial dynamics of groundwater management. For this purpose, the analysis is based on the theoretical and methodological framework provided by the Multi-Scale Analysis of Societal and Ecosystem Metabolism for water use analysis (*Giampietro et al., 2009; Madrid et al., 2013*). Time series data regarding the TAMA water budget are analyzed in relation to other socioeconomic variables and spatial information on groundwater management. These quantitative approaches are complemented by a review of the literature and planning reports, interviews, and participatory observation of water management meetings.

3.1 *Societal metabolism*

The concept of societal metabolism refers to the processes of appropriation, transformation and disposal of energy and materials to sustain socio-ecological systems (*Martinez-Alier & Schlüpmann, 1987; Giampietro et al., 2011*). These are understood as complex hierarchical

[3] http://www.azwater.gov/azdwr/WaterManagement/AMAs/TucsonAMA/TAMA_GUAC.htm

systems operating at multiple levels of organization and different spatial and temporal scales (*Allen, 2008*). The functioning of such a system is investigated at three analytical levels: the whole social system extracting resources and disposing wastes (level n), the different sectors of the system among which resources are distributed (lower levels n-x), and the environmental context that provides services and is impacted by these activities (upper levels n+x). While ecosystem processes and integrity pose the external constraints for feasible societal metabolic patterns, the internal constraints are imposed by institutional rules and cultural values. These constraints show up as non-linear interactions between and within levels. When specifically focused on water use, the approach is known as water metabolism (*Madrid et al., 2013; Madrid & Giampietro, 2015*) and addresses the interplay between the water cycle (n+2), impacts on ecosystem and their water dependency (n+1) and society (n).

The methodological approach used is the Multiscale Integrated Analysis of Societal and Ecosystems Metabolism (MuSIASEM), an environmental accounting scheme applied for the water-energy-land-food nexus assessment (*Giampietro et al., 2014*). It builds on the flow-fund model of *Georgescu-Roegen (1971)* to generate multi-level matrices that contain and connect different types of variables. Fund variables are those that remain the same or that we want to conserve during the analytical timeframe; they describe the structure and size of the system. Flow variables are the resources used, or products generated, to maintain structural fund elements. Typical social fund variables are land used, human activity and infrastructures. Ecological funds are biodiversity, soils or hydrologic patterns.

While most environmental accounting schemes consider natural resources to be stocks, there is a fundamental difference between the treatment of funds and stocks in MuSIASEM, which differentiates between renewable and non-renewable resources (*Giampietro & Lomas, 2014*). A flow of water, energy or wood can come from a fund if it is extracted under renewability rates (like sustainable managed forestry or sustainable aquifer yield) or from a stock if it is depleting non-renewable resources at human scales like fossil fuels or aquifers reserve. Flows and funds are quantified in absolute terms (extensive variables) on a multi-level basis aggregating from lower levels (households, specific economic activities) to the whole social system. The combination of flows and funds variables generates indicators (flow/fund, fund/fund intensity ratios) that allow a comparison of metabolic patterns of resource use. The approach to the interphase of socio-ecological systems is twofold: on the one side quantitative, through the analysis of environmental impacts of resource extraction and waste disposal, and on the other side qualitative, through the analysis of the institutional rules and policies that shape these physical interactions (*Cabello et al., 2015*).

3.2 *Application to the Tucson basin*

The methodology was deployed in four steps. We first analyzed the evolution of water flows in the TAMA water budget, using a 25 year long data series for the period 1985 to 2009-10, disaggregated per source and sector for the whole basin. The series and combined water sources per sector were plotted in an interactive visualization type Icicle tree[4] using the Quadrigram software (www.quadrigram.com). Table 1 shows the variables used and Table 2 lists the data sources; all the graphs and tables presented in the results section were produced using data from these sources. We maintain the same nomenclature for water flows as for the water budget.

Table 1 - Water metabolism variables for the Tucson basin

	Extensive	Unit	Description

[4] https://philogb.github.io/jit/static/v20/Jit/Examples/Icicle/example2.html

	variables		
Flows	**Water sources**	**AF/ Mm^3**	
	CAP direct		Water from CAP that is directly used without previous recharge
	Groundwater in-lieu		Water from CAP that is used instead of pumping groundwater
	CAP recovered		Water pumped from aquifers in exchange of previously recharged CAP water
	Reclaimed		Wastewater effluent directly reused after treatment
	Reclaimed recovered		Water pumped from aquifers in exchange of previously recharged wastewater effluent
	Groundwater		Water pumped from aquifer
	Overdraft		Difference between total water pumped from aquifers and natural + artificial recharge. Calculated in the water budget on a basin wide basis
	Water use		Sum of total gross water use per each of the sectors
	Municipal		Water supplied by municipal providers for residential and non-residential use. It is composed by large provider's residential, large non-residential (Other urban services), lost and unaccounted, small providers, exempt wells and deliveries to individual. Exempt wells are estimated as 1 AF of annual demand per every four wells
	Mining		Water withdraw by mines
	Other economic sectors		Water used by economic sectors outside the municipal supply network: dairy and feedlot; sand and gravel extraction; electric power generation; golf and turf facilities; other
	Agriculture		Water used by agricultural sector
	Indian nations		Water used by Tohono D'Oham nation and Pascua Yaqui tribes
Funds	**Human activity**	**Hours**	Population in a given year per 365 days per 24 hours
	Households		Hours of non-paid activities, calculated as the difference between paid work hours and total human activity. The required data to disaggregate this sector are the Time Use Surveys which are only available in the United States at the national level but not at the state level.

	Paid Work		Hours employed in paid work activities. Calculated as the sum of employment in each sector per average
	Land uses and covers	**Miles/ acres/ hectares**	
	Forest		Sum of deciduous and evergreen forest surface categories of the National Land Cover Databased (NLCD)
	Shrubs		Shrub category of the NLCD
	Water bodies		Sum of water bodies, woody wetlands and herbaceous wetlands of the NLCD
	Barren land		Barren land category of the NLCD – mines area
	Cattle grassland		Sum of grassland and pastures categories of the NLCD
	Mining		Digitalized over orthophoto 2014
	Urban		Sum of high, medium and low density and open space categories of the NLCD
	Crops		Crop category of the NLCD
	Intensive variables		
Fund/ fund	Employment	%	Hours in each economic sector out of total working hours in a year
	Dependency ratio	%	Hours of unpaid activities (households) out of total hours in a year
	Land occupation ratio	%	Land employed in productive human activities out of total land minus hard rock (not available land)
	Housing units density	Housing number/ $mile^2$	Number of houses per land unit
Flow/ fund	Income per capita	$/capita	Gross income per capita in a year
	Gallons per capita day	Gallons/ cap*day	Municipal daily water demand divided by total population served
	Water use density	Acrefeet/ acre	Water use per acre of land used
	Water use intensity	Gallon/ hour	Water use per hour of total human activity
	Crop prices	$/lb	Annual price of agricultural commodities received by farmers

Table 2 - Data sources

Data Type	Sources	Links (Accessed February 2015)
Rainfall	National Weather Service Forecast Office	http://www.wrh.noaa.gov/twc/climate/reports.php
Shallow groundwater areas	Pima Association of Goverments	http://gismaps.pagnet.org/subbasins/#/MapUser
Water table levels	Pima Association of Goverments	http://gismaps.pagnet.org/subbasins/#/MapUser
Wells inventory	Arizona Water Resources Department	https://gisweb.azwater.gov/waterresourcedata/WellRegistry.aspx
Artificial recharge	Arizona Water Resources Department	http://gisdata.azwater.opendata.arcgis.com/
Long-Term Storage credits	Arizona Water Banking Authority	http://www.azwaterbank.gov/Ledger/defaultIntrastate.aspx
	Arizona Water Resources Department	http://www.azwater.gov/azdwr/WaterManagement/Recharge/default.htm
	Central Arizona Project	http://www.cap-az.com/index.php/departments/recharge-program
Water accounting areas	Pima Association of Goverments	http://gismaps.pagnet.org/subbasins/#/MapUser
Water budget	Arizona Water Resources Department	http://www.azwater.gov/AzDWR/Watermanagement/AMAs/TucsonAMA/TAMAOverview.htm#waterbudget
Demography, housing, income& employment	American Census FactFinder	http://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t#
Land covers	Multi-Resolution Land Characteristics Consortium	http://www.mrlc.gov/
Crops and prices	National Agricultural Statistics Service	http://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS

Next, to address structural changes that occurred since recharged CAP water began to be recovered, we analyzed the evolution of societal metabolism of water between 2000/01 and 2010/11. Our analysis included societal funds, land use and human activity, and water flows per end use sector. Land use and cover categories were aggregated from those of the 2001 and 2011 National Land Cover Databases. Human activity was calculated from the American Census demographic, economic and employment data for 2000 and 2010. Note that the methodology followed in both censuses is different, in that the former is an extensive one year inventory of the entire population while the latter contains the average variables of surveys to population samples during different years. Data for 2010 are averages of 5 years. Water uses per sector were averaged for the previous decade (1990-99 and 2000-09) in order to compare tendencies.

In the third stage, we analyzed the evolution of water conservation targets for the municipal and agricultural sectors. The different components of municipal demand were included in the water budget alongside the population served by these subcomponents (large municipal residential and none residential, small municipal and exempt wells). Gallons per capita per day were calculated by simple division of those variables. Agricultural demand was contrasted with precipitation and crop prices data. Precipitation time series for the weather station in the city of Tucson were obtained from the National Weather Service Forecast Office. Data for evolution of crop patterns and prices were obtained from the National Agricultural Statistics Service (available starting in 1996).

Finally, we conducted a spatial analysis of groundwater management. The analysis considered available GIS data for groundwater recharge and recovery sites, location of groundwater users and the changes in aquifer levels between 2000 and 2010. The latter were interpolated from point measurements via Inverse Distance Weighting using ArcGIS 10.1. Long-term groundwater storage credit data for each recharge area was only available for the AWBA credits. The long-term storage credits held by other institutions (about 50% of all long term credits) were inferred by combining the ADWR total accounting per owner updated in February 2015 (*ADWR, 2015a*), the annual status report of the TAMA recharge plan (*ADWR, 2007*) and data from CAP recharge sites (*CAP, 2015*). Being based on a series of assumptions, the estimates cannot be considered to be fully accurate, but can be deemed sufficiently well for the purpose of establishing a spatial reference regarding where the water is being stored.

3.3 *Collaborative research and participant observation*

Our interest in the research questions addressed by this chapter arose from a series of interactions with local stakeholders in regards to water issues in the Tucson basin. Our work is situated in a constructivist context to the perspective known as post-normal science (*Ravetz and Funtowicz, 1993*). We consider that sustainability science must pay especial attention to the question *who reframes scientific questions?* (*Filardi, 2015*). For that reason, we proceeded to design this work in an iterative manner. In the first phase (February-July 2013) we conducted a preliminary literature review, and an interview with a local water manager allowed us to frame a draft set of scientific questions that were presented, reframed and prioritized in a participatory workshop in April 2013 with participation of University of Arizona experts and local stakeholders. Key issues identified were:

- The effect that changes in the socioeconomic structure have over water demand.
- The effectiveness of TAMA Management Plans for achieving safe yield by 2025.
- The impact of the groundwater credit system on the present and future dynamics of the water budget in the Tucson Basin.
- The impact of groundwater dynamics on biodiversity conservation.

The bulk of the research was then conducted between November 2014 and March 2015, during which time we attended two regional water management meetings as participant observers — the Safe Yield Task Force meeting on January 23rd and the Groundwater Users Advisory Committee on February 28th, 2015 — where discussions were held regarding how regional planning is moving forward to face identified management challenges. Preliminary results were also discussed and validated with local stakeholders.

4. Results

4.1 *Evolution of water use*

In this section we explore the evolution of the TAMA as a socio-hydrological system since the approval of the GMA, linking changes in the institutional context to those in water use. The information presented here is based on a thorough review of water planning reports (*ADWR 1999, 2008, and 2010a; AWBA, 2013, 2014; Megdal et al., 2008; and TAMA, 1998*) in combination with data from the last update of the TAMA water budget until 2010. The data presented in *Figure 2*, using the Icicle visualization, illustrate the evolution of the different sources of water used in the whole Tucson basin (big upper square) and per sector (four small lower squares) in 1990, 2000 and 2009 (different colors are used each water source). In addition, *Figures 3* and *4* show the temporal evolution of the data.

1980-1990: Responding to challenges. While the CAP was being constructed, the first TAMA MP boosted water conservation programs by setting conservation goals for each sector. A target of 140 gallons per capita day (GPCD) was set for the municipal sector. The Base Conservation Program (BCP) approved for the agricultural sector established groundwater allotments based on irrigation efficiency targets[5], water duties[6] and water duty acres for the reference period of 1975 to 1979. Specific programs were developed for each type of industrial use permit. Mandatory water use reporting requirements were set and water accounting started in 1985. As illustrated in Figure 2a, all sectors relied almost exclusively on groundwater during this period, with the exception of some reclaimed water used by the municipal and agricultural sectors. Indian nations represented a small share of total water demand (1%) while mining was already relevant (Figure 4). The municipal sector had already become the biggest water consumer, steadily growing from 41 to 48% of total water demand during this period, while agriculture fell from 42 to 32% of overall water demand as a result of the gradual reduction in irrigated acres (see *Figure 3*).

1990-2000: Adapting. CAP water arrived to Tucson in 1992 (*Figure 3*). One of the main objectives of the 2nd MP was to overcome legal, institutional and structural barriers for utilization of new supplies from CAP and reclaimed water (*Megdal et al., 2008: 90-91*). During this period, most of the laws, programs and institutions in place to firm CAP water (for instance AWBA or CAGRD) were created as described in section 2.2. In the TAMA, the regional recharge plan was enacted as a new device for achievement of the safe yield goal by storing excess CAP water underground (*IPAG, 1998*). While the second MP renewed conservation programs, it also introduced flexibility measures in both the agricultural sector — to facilitate adaptation to the evolution of market for agricultural products —, and in the municipal sector for small providers who had encountered difficulties achieving the 140 GPCD target. For agriculture, a highly controversial efficiency target of 85% was set during this period. In addition, farmers who did not use their entire groundwater allotment in one year were allowed to "bank" this water as "flexibility credits" for future recovery (*Fleck, 2013*).

The city of Tucson started using CAP water for municipal supply in 1993. It was treated to drinking standards and delivered through a water distribution system that had only conveyed groundwater in the past. Due to the different chemical composition and pH of the CAP water, it dissolved and re-mobilized mineral concretions that had accumulated inside the pipes over the years, resulting in unappealing brown water coming out of the taps. The consumer protests that ensued led to abandonment CAP water for direct municipal use after less than 2 years. Tucson reverted to groundwater use while alternative solutions were being developed to enable indirect use of the CAP water for the city's water supply.

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[5] Efficiency defined as final water uptake per water delivered

[6] Calculated for each farm unit as irrigation requirements divided by total acres planted from 1975 to 1979 and multiplied by irrigation efficiency target.

Groundwater use by the mining sector increased significantly in 1991 to 8449 AF (10 Mm^3), remaining constant for the rest of the decade. According to the TAMA water budget, the groundwater in-lieu program started in 1992, rerouting direct CAP use to agricultural production (albeit not in a significant share until 1998), in exchange for the accumulation of long-term storage credits. Municipal providers subsidized the cost of part of this CAP water to farmers accruing the generated long-term credits (LTSC) in exchange for municipal groundwater pumping for residential water supply. The result of all these parallel processes was that the annual overdraft of groundwater diminished in 1993 but began increasing again a year later to peak at 189,916 AF (154 Mm^3) in 1997 (*Figure 3*).

(Figure 2 to appear here)

Figure 2- Sources of water used for the TAMA (upper half of the figure) and per sector (lower half) in 1990 (A), 2000 (B) and 2009 (C)

(Figure 3 to appear here)

Figure 3 - Evolution of water use per source and groundwater overdraft

(Figure 4 to appear here)

Figure 4 - Evolution of water use per sector

2000-2010: Complexifying. The 3rd MP inaugurated the decade of groundwater storage and recovery. Between 2001 and 2010 7 different sources of water were used in the Tucson AMA (see Table 2 and Figures 2b and 2c): groundwater, direct use of CAP, CAP in lieu, CAP recovered, reclaimed, reclaimed recovered as well as small quantities of surface water or low quality groundwater. While all sectors diversified their sources of water, the greatest change observed throughout this period was in the municipal sector, which by 2009 was using 60% of recovered CAP water, along with water from five different other sources. The recharge infrastructure and institutional framework created in the previous decade enabled the increasing municipal demands to be met, while simultaneously replacing direct groundwater use with recovered CAP water, so that the annual groundwater overdraft started to decrease significantly (Figure 3). Another noteworthy change was the reallocation of CAP water to the Indian nations and tribes following the Arizona Water Settlements Act of 2004. As observed in Figure 4, the agricultural sector drives overall variability in demand and, in turn, the instability of annual groundwater withdrawals. In addition, conservation programs were substantially softened during the 3rd MP, substituting conservation targets with the Best Management Practices program (BMP) that tailors the improvements towards conservation to each end-user, instead of setting a common goal.

4.2 *Evolution of societal metabolism*

In this section, with the aim of widening the discussion from water flows to other relevant dimensions of sustainability, we compare two snapshots (for 2000 and 2010) of the societal metabolism of water in the Tucson basin. Table 4 shows societal funds and moving average water flows for the two decades, alongside some metabolic indicators (intensive variables). Indian nation demand has been disaggregated and added to final subsectors (municipal, agriculture, and other economic sectors).

During this period, the land occupation ratio increased by two percent, driven mainly by the urbanization of shrubland areas, with an average annual growth ratio of 3.3%. In addition, the housing density rose from 1 to 1.2 houses per square mile. A significant fact is that the small surface area devoted to agriculture surpassed that allocated to large-scale mines. Conifer forested areas decreased by 11.7%, mostly in the Northwest Catalina peaks. A positive environmental change was the increase in surface area of water bodies by 40%, especially wetlands, partially because of the groundwater recharge sites but also due to riparian restoration projects.

In regards to human activity, the ratio of total working hours to total human activity increased despite increased unemployment in many urban areas, especially for those with lower incomes such as South Tucson, Summit, Three Points and Drexel Heights. This was compensated for by jobs generated in new urban areas, resulting in an overall employment rise of 13%. The economic model of Arizona has been based on the services sector coupled to urban growth (*Jacobs, 2009*). Indeed, the services sector grew more in terms of employment generation, particularly in education, health, professional science, recreation and food services. This unveils the role of the University of Arizona as an important economic driver for the region. In addition, Arizona is famous as being a destination for winter seasonal retirees who help to boost the services economy. The demographic evolution shows two clear trends: a process of ageing and a permanent domination of the group aged between 18 and 25. On the other hand, the building and real estate sectors lost importance in regards to fraction of the total economy, although both grew in absolute terms. Agriculture and mining are smaller, but yet increasing sectors. The overall income per capita increased by 27%.

Table 3 - Societal metabolism evolution during the 3rd MP

		Land use (miles^2)			**Human activity (10^6 hr)**			**Water use (10^3AFY)**	
		2000	**2010**		**2000**	**2010**		**2000**	**2009**
n+2	Tucson basin	3871							
n+1	Forest	162	145						
	Shrubs	3235	3216						
	Water bodies	7	10						
	Barren land	17	16						
n	Land occupation	451	486	Total human activity	6810	7990	Gross water use	306	346
n-1				Paid Work	501	657	Economic sectors	197	209
n-2	Crops	42	43	Agriculture	1.4	2.3	Irrigation	97	110
	Grassland	52	53				Dairy & feedlot	0.07	0.1
	Mining	NA	50	Mining	2.5	4.4	Mining	39	34

	Urban & developed	307	340	Building	38.7	40	Sand & gravel	4.1	3.9
				Manufacturing &Retail	140	163	Electric power	2.1	3.5
				Real State & financial	29	35	Golf & turf facilities	7.4	8.4
				Other urban services	254	362	Other urban services	39	43.5
				Government & military	35	50	Other	7.2	5.3
n-1				Households	6308	7333	Residential	109	136
n	Land occupation ratio (%)	0.19	0.21	Dependency ratio (%)	93%	91%	Water use density (AF/acre)	1.06	1.11
	Housing units density (houses/ mile^2)	1.0	1.2	Income ($/cap)	19,959	25,454	Water use intensity (Gallon/hour)	14.67	14.11

Most water uses are positively correlated with the evolution of the employment pattern. For instance the sand and gravel water use decreased with the declining weight of the building sector in the overall economy. Main water use increases were observed in residential and urban economic activities (non-residential municipal), in parallel to the growth of the services sector and the expansion of urban areas. Mining is the only activity that grew in employment without mirroring increments in water flows, thus becoming more efficient per hour of human activity. On the other hand, agriculture augmented its average consumption by 13% during this decade. Overall water efficiency improved per hour but decreased per acre (from 2032 m^3/ha in 2000 to 3432 m^3/ha in 2010) linked to the process of densification of urban areas. From a sustainability perspective, it is important to point out that the TAMA water management system depends on two external resources:

i) Imports of practically 100% of food requirements since agricultural production is mainly devoted to cotton and cattle-feeding products.
ii) Low-cost energy from the Colorado dams, and the availability of the Navajo Generating Station for pumping CAP water and is lifting it 2900 feet from the Colorado to South Tucson city.

Regarding the latter, the CAP is the major single energy consumer in Arizona, with an annual consumption of 2.8 million megawatt-hours (*CAP, 2010*). Ninety percent of this electricity is supplied by the Navajo Generating Station coal-fired power plant in Page, which also supplies energy to the Tucson Electric Power Company. According to *Eden et al. (2011)*, the estimated energy intensity of CAP water when it reaches Tucson is 3,140 KWh/AF (2.54 KWh/m^3), which is four times larger than the average for groundwater pumping. Interestingly, the current (2014) rate for CAP water is only 140 $/AF (0.11 $/m^3), thanks to good energy efficiency management and the revenues obtained from sales of surplus NGS energy (*Eden et al. 2011*). As shown in Table 4, water used for electric power generation within the Tucson basin is a small but increasing share of the overall budget. Increasing regulations over emissions and shortage predictions in the Colorado River basin are pinpointed as vulnerabilities of the system to an increase in energy prices (*Cullom, 2014*).

4.3 *Is water conservation curbing demand?*

As described in section 4.1, the use of water conservation programs was a core management device during the first three MPs, because such was specifically required by the GMA. Nevertheless, MP goals and requirements have evolved towards increasing flexibility and adaptability for each individual end-user, to the point that their effectiveness is currently being questioned (*Megdal et al., 2008; Fleck 2013*). The general accepted view is that demand is decreasing because of a reduction in the GPCD in the municipal sector. In what follows we examine available data from the TAMA water budget. The data are given for entire sectors, and are only disaggregated for municipal demand into the categories shown in Figure 5. Data for agricultural uses only indicates overall demand and irrigable acres, but does not identify actually irrigated land. The problem with this data format is that it does not allow us to distinguish the effects of conservation programs on demand evolution from other drivers like climate, landing use or market changes (*Megdal et al., 2008*).

As shown in Figure 5, 58% percent of municipal demand is residential, supplied by large water providers within what are called service areas. This demand grew continuously until 2002, whereupon it stabilized. From 2007 to 2009, overall large provider residential demand decreased by 1223 AF (1 Mm^3), and the GPCD also decreased to 97 GPCD (370 lpcd) in 2009 (down from 122 GPCD in 1989). On the other hand, large-provider non-residential deliveries increased during the last decade, and lost and unaccounted municipal water uses remained stable. Small providers and exempt wells[7] are a very small share of the total municipal demand, but have very high GPCD (181 and 645 GPCD per capita in 2009 respectively). The significant decrease in overall demand between 2007 and 2009 comes from the removal of one category from the overall accounting: delivery to individual users that are described as non-irrigation users with conservation requirements, including turf and cooling facilities. Between 2000 and 2009, the population in the TAMA region increased by 173,864 people, but decreased in 2010 (for the first time on record). The increase did not mirror increases in large-scale domestic demand. Updated data presented by the ADWR at the GUAC meeting[8] of February 2015 confirmed the decreasing tendency in domestic demand, both in absolute and relative terms.

(Figure 5 to appear here)

Figure 5 - Evolution of total municipal water demand, identifying demand categories and GPCD

The agricultural sector is a different and very complex reality. The GMA limited the possibility of increasing irrigable acres. Since 1995 these have remained relatively stable at around 36,200 acres (14,500 has, 1% of the total TAMA area), when 6210 acres of irrigation grandfather rights were bought by Tucson water and transformed into non-irrigation rights (*ADWR, 2015b*). There is no available data on actual irrigated acres per year per irrigation district, nor of the evolution of irrigation systems that could allow an assessment of the effects of conservation programs on agricultural demand. Average agricultural efficiency has increased from 50% to 80-90% as a result of the BMP program (*ADWR, 2015b*). Nonetheless, the literature is skeptical in regards to these results (*Wilson & Needham, 2006; Bautista et al., 2010*). A very generous water allotment from the

[7] Estimated as 1 AF of annual demand per every four wells.
[8] http://www.azwater.gov/azdwr/WaterManagement/AMAs/TucsonAMA/documents/FinalAgenda-TucsonAMAGUAC2.26.15.pdf

beginning and the introduction of flexibility accounts are pointed out as primary causes for their ineffectiveness. According to these authors, conservation programs for the agricultural sector are so flexible that most farmers didn't even change to the supposedly more flexible BMP program but, rather, remained in the initial Base Conservation Program.

Wilson and Needham (2006) and *Fleck (2013)* show rather than the conservation programs of the GMA, it is commodity prices (especially for cotton and alfalfa, which are water intensive crops) and rain that are the main explanatory factors driving agricultural water demand variability in central Arizona. *Figures 6* and *7* show the evolution of agricultural water use, precipitation and the prices of the three main crops planted in the Tucson basin (cotton, hay and wheat). Agricultural demand is highly variable on a year-to-year basis, but fluctuates around a rather stable average. Until 1998, demand had a negative correlation with precipitation (Pearson -0.63) but since then, this relation is much less obvious. The 1996 Federal Agricultural and Improvement Reform Act decoupled crop prices and government subsidies from production, and increased planting flexibility (*Frisvold, 2007*). Separating out the composite effect of this legislation from the evolution of crop prices and precipitation would require an econometric model that is outside the scope of this paper. Nevertheless, *Figures 6* and *7* show that from 1996 onwards, the peaks in prices (especially for cotton) mirror peaks in water demand even when precipitation is not below the mean (Pearson 0.45 for cotton price, 0.3 for wheat, 0.44 for hay and -0.2 for precipitation). In 2008 peak water demand for the decade coincided with both lower precipitation and peak prices for all crops.

(Figure 6 to appear here)

Figure 6 - Agricultural demand and precipitation

(Figure 7 to appear here)

Figure 7 - Agricultural demand and crop prices

From the analysis in the previous sections we can conclude that:

i) Overall water demand trend in the Tucson basin has continued to increase over the past 25 years although the pace of increase has slowed by one third during the last decade (with respect to 1990-2000);
ii) Large municipal providers are making progress both in terms of cutting domestic demand as well as reducing groundwater overdraft;
iii) For the other water use sectors analyzed, conservation has not been very effective as a demand reduction strategy; and
iv) Agriculture, being highly affected by crop prices and precipitation, drives annual variability of overall Tucson basin demand and groundwater use.

The capacity to continue curbing demand in the future by increasing conservation is considered small (*Megdal, 2015; ADWR, 2015b*). Instead, the ADWR plans to turn the core management strategy for the forthcoming 4th MP to supporting regional cooperation towards achieving safe yield during the next 10 years (*ADWR, 2015b*).

4.4 *A spatial assessment of groundwater management*

Table 4 - Water resources (AFY)

08-2010	nds	Precipitation (mm)	209 – 670
		Average	379
		Average natural recharge	81,964

Undoubtedly, the main management strategy for achieving the TAMA goal of safe yield is the substitution of groundwater overdraft by

		CAP inflow	197,289
		Reclamation	50,904
		Artificial recharge (CAP + reclaimed)	202,201
		Recovery	124,118
		Long-Term Credits	798,844
		USF-CAP	630,545
		USF-Effluent	89,583
		GSF	78,716

Undoubtedly, the main management strategy for achieving the TAMA goal of safe yield is the substitution of groundwater overdraft by other resources. Taken together, the total volume of CAP water and wastewater is three times the groundwater available through natural recharge. From 1993 to 2009, an average of 53% of total artificial recharge was recovered annually for municipal and industrial uses, 1.6% lost through evaporation in recharge sites, 7.4% remained as cut to the aquifer, and the rest was stored as LTSC. The continuous increase of recharge capacity coupled with the renaming of most municipal groundwater withdrawals as recovered water, resulted in a technical achievement of safe yield on a basin-wide scale (SYTF, 2015). However, the spatial distribution of this achievement is not homogenous.

As depicted in Figure 8A, there are 12 USF sites in the Tucson AMA — 7 recharging reclaimed water and 5 recharging CAP water — plus 6 GSF located in agricultural sites. Most of the recharge occurs in the Avra Valley and Pima mine road CAWCD sites, and uses CAP water. Most of the recharge of effluent takes place north of Tucson city. Groundwater recovery is mostly done by Tucson Water in the area of influence of the Avra Valley (CAP) and Sweetwater (effluent) recharge sites and delivered to the city (*ADWR, 2010a: 52*). However, 90% of recovery and withdrawal wells are scattered throughout the municipal service area, with an important concentration in the large Mission and Sierrita Mine sites (located in southeastern Pima County), which are spatially disconnected from recharge areas (see *Figure 8A* and *B*).

Arizona statutes require that groundwater recovery for municipal providers be located either within a 1 mile of a USF site or in areas where groundwater decline is less than 4 ft/year (1.22 m/year). This limitation does not apply to those municipal users that join the CAGRD to meet the AWS requirements and can withdraw groundwater anywhere within their service or member land (ML) areas. This was seen by municipal providers to be a major equity problem in the region (*Megdal et al., 2008: 24*). Indeed, many of these providers have transferred their LTSCs to the CAGRD to enjoy the same advantages (*ADWR, 2010a: 55*). As observed in Figure 7B, the CAGRD service area embraces all municipal providers while new member lands have three hotspots in northwest Catalina Mountains, eastern Vail and south Green Valley, all primary development areas within the TAMA. In 2009, 50% of groundwater (not recovered) pumping for municipal use was allocated to new developments, 37% as groundwater allowed under the AWS rules and 13% as excess groundwater that has to be replenished by the CAGRD.

(Figure 8 to appear here)

Figure 7 - A- Recharge sites and capacity; B- location of water users; C- accrued LTSCs per site; D-evolution of groundwater levels between 2000 and 2010 (feet) and shallow groundwater areas

The last piece of this complex puzzle is the Long-Term Storage Credit system. The most recent update of credits accrued in 2014 showed a total of 1.4 M AF (1129 Mm^3, nearly four times total water demand in 2010), an increase of 80% since 2009 (see Table 5). During the last five years, the AWBA has been especially focused on recharge within the Tucson basin, accounting for 50% of the total LTSC. Other major owners are Tucson Water (15.6%), CAGRD (8.6%), Tohono O'odham Nation (6.2%), the Bureau of Reclamation (5%)

and the Rosemont mine company Augusta Corporation (3%) (*ADWR, 2015a*). In addition, there are 18 other entities owning less than 2% of the credits including small municipal providers (Marana, Oro Valley, Vail, Metrowater) and one irrigation district. As shown by Figures 8 C and D, accumulation of credits has been responsible for the recovery of aquifer levels in Avra valley and along Pima mine road. The rate of annual recovery of LTSC is around 1%. These credits can be recovered from anywhere within an AMA as long as consistency with management plan goals is maintained, and the recovery is inside or within three miles of the service area of a municipal provider or irrigation district. The credits owned by AWBA have the purpose of assisting municipal and industrial uses in case of shortage, meeting Indian water rights and fulfilling management goals; they have a specific recovery plan (*AWBA, 2014*).

There is no available spatial data online that provides an exact accounting of recovery and pumping. Nevertheless, water table levels are monitored and their evolution from 2000-2010 is displayed in Fig 8 D[9]. It can be seen that the areas where groundwater credits are being accrued are those undergoing water table rises of up to 60 feet (18 m). Groundwater levels in the central part of the city of Tucson have also been rising, since the recovery in Avra Valley enabled Tucson Water to turn off its central well (that was driving the major cone of depression and land subsidence in the TAMA). On the other hand, few areas of water table decline remain. Peak declines of up to 71 feet (21.6 m) are observed in north-east Oro Valley area where the major use sector is urban. The second relevant drawdown area is the southern Green Valley where some of the largest mines coincide with new developments and a large irrigated area, all of which rely mainly on groundwater. In addition, the eastern area of Vail has experienced similar average decreases of 44 feet (13 m) in the last ten years. As can be seen in Figure 8D, the mountain ranges around the Santa Cruz valley are home to the largest riparian ecosystems in what are known as shallow groundwater areas (*SGWA, PAG, 2012*). These are sustained by natural recharge over high bedrock, but many connect to areas of the aquifer with declining levels. Within the Tucson basin there are 20,537 acres of SGWA connected to wider systems (*Figure 8D*), 46% of which overlap with areas of the aquifer having declining levels. It is noteworthy that there have been very few areas showing declines over 40 feet during the ten years monitored and in which recovery was forbidden.

In 2013, the ADWR launched a public consultation regarding a proposal named Enhanced Aquifer Management (*ADWR, 2013*) that aimed to encourage groundwater recovery nearby recharge sites. It consisted on a calibration of percentage cuts to the aquifers depending on the distance to the recharge site: 0% within 1 mile buffer, 10% after 1 mile but within the AMA, 20% outside of the AMA. All comments to the proposal were negative arguing that any disincentive to use CAP water would turn users towards groundwater again, resulting in increased water costs to customers or negatively affecting the emerging LTSC market (*Brooks, 2013; Tucson Water, 2013*). Alternative proposals included limiting pumping in areas with declining groundwater levels, limiting the allowable declining rate, or setting a tax based on observation of impacts in declining areas (*Brooks, 2013*). The final outcome of the discussion was twofold: 1) a requirement to improve information, and 2) a proposal to construct more pipes to allow CAP water to be delivered to more areas within the TAMA. On one hand, the Safe Yield Task Force recently proposed subdividing the Tucson basin into seven water accounting areas (WAAs) as a tool to improve water planning (*ADWR, 2015b*). On the other hand, water providers are also working on cooperative Wheeling Programs with the aim of building the infrastructure required to deliver CAP water to all urban service areas experiencing declining water tables[10].

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[9] The figure shows interpolated data for monitored wells between September 2009 and March 2010. For a detailed visualization of wells location and levels visit the interactive map of Pima Association of Government http://gismaps.pagnet.org/subbasins/#/MapUser

[10]

5. Discussion: Growth, sustainability and spatially neutral groundwater management

In this chapter, we have examined the evolution of water metabolism with particular focus on the changes induced by the arrival of CAP water to the TAMA, and with the aim of contributing to the debate regarding water management strategies to achievement sustainability objectives in the Tucson basin. The goal of safe yield imposed by the Groundwater Management Act has been pursued by a combination of i) reducing demand for existing uses through conservation practices (i.e. improving efficiency), ii) limiting the expansion of new demands and iii) bringing new resources to the region to substitute for the use of groundwater. Dissecting the effect of each of these strategies is a difficult task, since multiple interconnected layers of regulations have been overlaid during the past 30 years without a discrete assessment being carried out. Here, we have analyzed the available data and pinpointed limitations in information.

We have shown that construction of the CAP was a tipping point in the water metabolism of the area, in the sense that it brought about a drastic reconfiguration and diversification of water sources for the different sectors, while fueling the economy. This was enabled by increasing infrastructural and institutional complexity to make full use of what are deemed renewable resources from the Colorado River. Infrastructural complexity was deployed through a system of new facilities for recharge and storage, and by constructing new wells and pipelines to transport recovered water to the denser urbanized Tucson area. Institutional complexity was achieved through a series of new laws, programs, institutions and cooperative agreements that multiplied the decision-making nodes of a decentralized governance network.

Regarding the control of water demand, we have shown that, despite population growth, large municipal providers have managed to stabilize urban demand by reducing demand per capita. Therefore, if not reducing overall demand, at least the sector is now balancing savings against new demand. Other municipal components do not seem to be making significant progress and the apparent slight reductions in total municipal demand are mainly due to a change in accounting rules. Further, conservation programs for agriculture seem to not seem to be having the foreseen impact. On an annual basis, irrigation demand varies about a rather stable average, driving peaks in both the total Tucson basin demand and groundwater pumping on dry years and/or periods of high commodity prices. Since 2000, the Indian Nations have become significant players in the overall budget. Total water demand in the Tucson basin has grown continuously, although a slowdown in the pace of growth was observed from 2000 to 2010, in comparison with the previous decade. CAP water has partially replaced groundwater withdrawals, therefore contributing to overdraft reduction.

In regards growth limiting measures, the binding non-expansion rule for agriculture has been effective in controlling demand. Mines and other economic sectors have no limits imposed on their permits. The data indicate that mines have become more efficient in water use, but that their local impacts on water table levels are still very significant. Water uses are in general coupled to the trajectory of evolution of the economic sectors with a clear predominance of urban services. The Achilles heel of Arizona water problems is that of limiting growth in the urban sector, since the dominant economic model is tied to urban expansion (*Akhter et al., 2010*). All attempts to set constraints regarding groundwater overdraft that might affect development have been systematically thwarted. From 2000 to 2010 the development sector lost weight in the economy, but this is perceived as associated with the volatility of the housing market after 2008. According to the CAGRD

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http://www.azwater.gov/azdwr/WaterManagement/AMAs/documents/SAWUA_TW_EAMPresentation06042014.pdf

Operation Plan 2014, the annual rate of membership drastically dropped since 2009, and so did their replenishment obligations. Most land lots have not been built upon and current projections show construction increasing over the next 10 years and peaking in 2021. Coupled with this, municipal water demand is projected to grow until 2045 (*CAGRD, 2014: 49-51*) by nearly 29.000 AF (35 Mm^3) in the Tucson AMA. It is however the lowest of the projections for the three CAGRD AMAs.

The lack of spatial disaggregation of the water budget makes it difficult to assess the extent to which improvements in efficiency in some urban areas are enabling growth in others. What seems clear is that there is a disconnection between recharge and recovery in some areas and that local impacts on the water table are still important. The technical achievement of safe yield at a basin level is uneven and there are wide areas in which overdraft continues to occur, especially in new development locations. Larger biodiversity hotspots are dependent on shallow groundwater, and some of them are partially located over areas with declining aquifer levels.

The new category of *recovered water* enables continued mining of groundwater without being properly accounted for in the overdraft. A proper accounting should reflect which part of the recovered water is actually CAP, which is reclaimed water (for instance the water that Tucson Water transports from Avra Valley to the city), and which is not (all the water recovered outside the area of impact of the recharge site), and should split the accounting of safe yield into different sub-regions according to that. The WAAs project is a good step in this direction. The regional network for water governance is aware of the impacts of the ill-defined spatial management strategy and is negotiating solutions. While it was initially proposed to constraint recovery near recharge, it seems instead that the final bet is for bringing recharge close to recovery through an expansion of the CAP infrastructure to reach more areas within the TAMA. Some have argued this is a straightforward solution to the current depletion problems (*Tucson Water, 2013*), but at the same time this view may not properly account for the expected shortage of Colorado water acknowledged by CAP managers. The AWBA recovery scenarios until 2024 for M&I and Indian uses in the TAMA can be largely met with 66% of its actual storage (*AWBA, 2014: 46*). The main recovery mechanism that has been proposed is the exchange of short-term annual credits of municipal providers for LTSCs accumulated near recharge sites (*AWBA, 2014: 55*). Agriculture has low priority access to CAP water and thus it is the most vulnerable sector to potential Colorado water shortages. Nevertheless, it has grandfathered rights that could again increase the pressure in regards to use of groundwater. The AWBA recovery plan does not mention safe yield at all, and so far there is no assessment of how recovery of the different credits by other different owners would impact the management goal.

In conclusion, the problem of how to reconcile the positive and negative impacts of urban growth remains the eternally unresolved debate in the Tucson basin and in the American south-west. Questions regarding potential physical, socio-economic or environmental limits to growth are not even “on the table” in Arizona. Water scarcity imposes a key limiting factor on the current urban growth-based economic model. However, an increasingly sophisticated governance regime has been devised to try to overcome this limitation. Safe yield is a laudable management goal that has triggered important changes in the water metabolism. Yet, the discourse regarding CAP as a renewable resource, and the use of creative accounting devices veil an unequal distribution of impacts and vulnerabilities derived from the spatially neutral approach to groundwater management. How this spatial inequity will be resolved is likely to characterize the sustainability debate over the next ten years, when the GMA is due to be assessed. Achievement of safe yield might be possible in most areas if new pipes are constructed to deliver CAP water to those locations, as long as no severe shortage in the Colorado River occurs. Whether this is a resilient or a ceteris paribus strategy that increases vulnerability will be seen over the course of the next decade. Any prior hypothesis would require a much more detailed analysis of disaggregated spatial data of water uses and sources that is not available at the moment.

Acknowledgements

The authors would like to thank the SWAN project for funding this work, its coordinator Dr. Frank Poupeau and the team leaders for pursuing the development of this book and supporting the students group with diligence. We would also like to acknowledge the generous time and thoughts of Linda Stitzer, Claire Zucker and Rita Bodner to help reframe the questions we look at in this paper, and those of the interviewees that helped us to understand the great complexity of the Tucson basin water system. Claire Zucker, Mead Mier and John Pope from the Sustainable Environment Program of the Pima Association of Governments have greatly contributed to this research by facilitating required spatial data, the transparency of this institution is exemplary. In addition, Sharon Megdal made excellent comments to this paper that substantially increased its accuracy and readability. Finally we would like to thank all the students and researchers in the SWAN project for the fantastic intellectual and cultural exchange, their patience and openness towards collective learning of what interdisciplinary and transdisciplinary mean.

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